NASA Technical Memorandum 103821

(NASA-TM-103821) INVESTIGATING COMBUSTION AS A METHOD OF PROCESSING INEDIBLE BIOMASS PRODUCED IN NASA'S BIOMASS PRODUCTION CHAMBER (NASA) 21 p CSCL 06K

N91-2[illegible]

Unclas

G3/54 0024[illegible]

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ACKNOWLEDGEMENTS

This work was performed under contract to the NASA Biological Research and Life Support Office, John F. Kennedy Space Center. We would like to acknowledge the contributions of Mary Ann Brannon, Cheryl Mackowiak, and Dr. Richard Strayer of The Bionetics Corporation and recognize Norm Petrulis and Dr. Sherman Chao of the Institute of Gas Technology* for rapid turn-around of analytical services. Additionally, we would like to recognize J. R. Puleo and Dr. S. C. White of The Bionetics Corporation, Drs. G. W. Hoffler and D. A. Tipton of the NASA Biomedical Operations and Research Office, and Dr. W. Berry of UCLA for critical review of the manuscript. This work was performed under NASA contract NAS10-11624.

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Abstract

The Controlled Ecological Life Support System (CELSS) Breadboard Project at the John F. Kennedy Space Center is a research program to integrate and evaluate biological processes to provide air, water, and food for humans in closed environments for space habitation. This project focuses on the use of conventional crop plants as grown in the Biomass Production Chamber (BPC) for the production and recycling of oxygen, food, and water. The inedible portion of these crops has the potential to be converted to edible biomass or directly to the elemental constituents for direct recycling. Converting inedible biomass directly, by combustion, to carbon dioxide, water, and minerals could provide a baseline for estimating partitioning of the mass balance during recycling in a CELSS. Converting the inedible biomass to carbon dioxide and water requires the same amount of oxygen that was produced by photosynthesis. The oxygen produced during crop growth is just equal to the oxygen required to oxidize all the biomass produced during growth. Thus, the amount of oxygen produced that is available for human consumption is in proportion to the amount of biomass actually utilized by humans. The remaining oxygen must be available to oxidize the rest of the biomass back to carbon dioxide and water or the system will not be a regenerative one. Human nutrition and water requirements, and the material requirements of other processes must also be taken into account. All this information is needed to determine the combination of crops and recovery processes to meet the crew needs and optimize mass flows in a CELSS.

Introduction:

The Biomass Production Chamber (BPC) is a crop production facility built in support of the Kennedy Space Center Controlled Ecological Life Support System (CELSS) Breadboard Project. It is an atmospherically closed, 113 m^3 controlled environment plant growth chamber with 16 m^2 of hydroponic growing area under electric lighting (Prince et al., 1987, Wheeler et al., 1990).

The biomass produced in the BPC can be divided into edible (EB) and inedible biomass (IB). The EB is composed of the seed and grain from crops such as soybean and wheat, and leaves of crops such as lettuce. The IB is composed of all the other plant components which are not normally included in the harvested food material such as the roots, stems, leaves, etc. Our data have shown that these IB components are a significant portion of the total plant mass. Specifically, the IB for lettuce is 10%, for soybean is 65%, and for wheat is 60%. However, it should be noted that not all of the edible biomass is digestable and will require further oxidation outside of the humans before it can be recycled back to the plant production unit.

Taking into account the severe limitations of space, volume, and energy that are inherent in space travel, serious consideration must be given to recycling the constituents of the IB. The Kennedy Space Center Breadboard Project is approaching this problem from two perspectives: a series of conversion processes for the biological production of edible material from inedible biomass; and the conversion of IB by direct combustion to establish baseline requirements for all conversion processes. This paper evaluates the direct combustion conversion option in greater detail while other conversion options are being addressed in other reports.

The complete combustion of the IB to carbon dioxide, water, and minerals is a direct way to recycle this material. Analysis of the major components of this material (ultimate analysis) can be used to project the amounts of carbon dioxide, water, and ash produced as well as the oxygen required during conversion of the inedible biomass. Heating value analysis yields a projection of the potential amount of energy produced during combustion.

The total amount of oxygen liberated during photosynthesis will ultimately be required to oxidize that biomass produced during photosynthesis to its initial state. If all the biomass produced, both EB and IB, were combusted, the oxygen produced during photosynthesis would be sufficient to oxidize it but would be totally consumed in this process. However, in a life support system designed for space travel with total mass closure, it is desirable that the maximum amount of biomass produced be utilized by the crew, in order to minimize the weight, volume, and energy required by a CELSS. Any biomass oxidation process outside of the crew food cycle reduces the efficiency of the CELSS in terms of direct crew life support. Therefore, increasing the amount of IB that can be converted to EB for the crew increases the efficiency of the system.

Materials and Methods:

Proximate, ultimate, and heating value analyses were performed on selected residues from three different BPC crops. This included: wheat leaves, stems, chaff, and roots; soybean leaves, stems, pods, and roots; and lettuce roots. The residues were oven-dried at 70°C and ground using a Wiley mill with a 2-mm screen. Portions of the wheat residue and the soybean residue were leached in deionized water at room temperature (23-25°C) for two hours using 50

grams of IB per liter of water with constant stirring rapidly on a magnetic stirrer. The leached residue was filtered in a buchner funnel and again oven-dried at 70^{o}C. The leaching was performed to extract water-soluble inorganic and organic compounds for further processing into a medium for edible, microbial biomass production and to return mineral components to the hydroponic solution (Garland et al., 1988; Brannon and Strayer, 1990).

Moisture and ash analysis were performed thermogravimetrically at 105^{o}C and 550^{o}C with a LECO* TGA-500 analyzer. Sulfur was determined by infrared detection of sulfur dioxide from a combusted sample using a LECO* SC-132 analyzer. Carbon and hydrogen were determined by infrared detection of carbon dioxide and water vapor, and nitrogen by thermal conductivity detection of nitrogen gas from a combusted sample using oxygen and catalysts with a LECO* CHN-600 analyzer. Oxygen was calculated by difference. The values reported for these analyses are the mean of three subsamples from each biomass sample. Heating value was measured in a Parr* bomb calorimeter. The values reported for heating value are the mean of two subsamples from each biomass sample. These analyses were performed by the Chemical Research Services of the Institute of Gas Technology*, Chicago, Illinois.

Formulas used to calculate conversions of carbon, hydrogen and oxygen, and are presented in Appendix I.

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Results and Discussion:

The results of the analyses of the raw materials along with the total inedible residue produced from each of the three crops are presented in Table 1. On the average, IB from different crops was comprised of about 40% carbon, 34% oxygen, 15-20% ash, with hydrogen, nitrogen, and sulfur generally being less than 5%. Heating values were also similar and ranged near 900 kJ/kg. The primary difference between the crops was the total amount of residue produced.

The calculated amounts of carbon dioxide, water, and energy produced and the amount of oxygen required (above the amount already present in the inedible biomass) from the three crops are presented as Table 2 (Appendix 1, equations 4-11). It is assumed that nitrogen and sulfur will be returned to elemental forms.

Calculated values of photosynthetic gas exchange from the total biomass measured for each crop as well as the requirements for direct combustion of the inedible biomass and net oxygen produced by each crop are presented in Table 3 (Appendix 1, equations 11-14). The gas exchange values assume all carbon dioxide assimilated is converted to carbohydrate, which would also give a mole for mole production of oxygen (from water during photosynthesis). Average gas exchange measurements made directly in the BPC yielded somewhat higher amounts of carbon dioxide uptake during crop growth: 64.5 kg for wheat and 37.4 kg for soybeans (Wheeler and Sager, 1990). The differences may be due to: respiration of plant material during air drying following harvest; the fact that not all carbon dioxide is fixed as carbohydrate but also as fats or proteins (this is especially true since the EB are contributing to empirical gas exchange values); the method used to calculate the mean gas exchange rate from carbon dioxide

Table 1. Analysis of Inedible Biomass from Three Crops Grown in the Biomass Production Chamber.[1]

	Wheat Residue	Soybean Residue	Lettuce Roots
% Ash	15.21	15.79	20.37
% Carbon	39.83	42.30	38.55
% Hydrogen	4.45	4.89	4.50
% Nitrogen	3.94	2.47	5.41
% Sulfur	0.10	0.05	0.14
% Oxygen	36.47	34.50	31.03
Heating Value (kJ/kg)	890	921	868

[1]Values represent percent by weight.

Table 2. Amount and Calculated Results of Complete Combustion of Inedible Biomass (Carbon and Hydrogen) from Three Crops Grown in the Biomass Production Chamber[1].

	Wheat Residue	Soybean Residue	Lettuce Roots
Total Inedible Biomass (kg)	26.8	12.6	0.14
Carbon Dioxide (kg)	39.1	19.5	0.20
Water (kg)	10.7	5.6	0.06
Energy (kJ)	23,806	11,622	120
Oxygen Needed (kg)	28.2	14.8	0.15

[1] Assumes that nitrogen and sulfur will be reduced to their elemental forms.

Table 3. Biomass, Carbon, and Oxygen Balance for Three Crops Grown in the Biomass Production Chamber.[1]

	Wheat	Soybean	Lettuce
Total Biomass (kg)	37.8	18.9	2.8
CO_2 (kg) fixed[2] (Biomass/0.68)	55.5	27.9	4.2
O_2 (kg)[3] liberated	40.4	20.3	3.0
O_2 (kg) to Oxidize Inedible Biomass	28.2	14.8	0.15
Net O_2 (kg) from BPC Crop	12.2	5.5	2.9

[1]Calculations based on assumption that all biomass is fixed as carbohydrate ($C_n(H_2O)_n$).

[2]Molecular weight of CH_2O/molecular weight of CO_2 = 30/44.

[3]Oxygen liberated assumed to be a 1:1 molar ratio with Carbon dioxide fixed.

uptake may overestimate the mean for the total light period; and the atmospheric leakage rate of 5 to 10% per day for the BPC (Wheeler and Sager, 1990). The fact that all carbon dioxide is not fixed as carbohydrate is evident from the fact that analysis has showed {carbon:oxygen:hydrogen} mass ratios of {41:39:5} for wheat and {45:34:5} for soybean (carbohydrate = {40:53:7}), which translate to values of 56.8 kg and 31.2 kg carbon dioxide fixed, respectively per crop.

The large differences in biomass productivity between the crops are affected primarily by the differences in total photosynthetically active radiation (PAR) provided. The total PAR in turn is affected by both the instantaneous irradiance and the length of the daily photoperiod. In related studies, Bugbee (1991) has shown that high irradiance and long photoperiods can be used to greatly increase the yields of wheat. In addition, by increasing the harvest index (the percent EB), the amount of IB can be reduced accordingly.

Leaching of the wheat and soybean residues (Tables 4 and 5) reduces the amount of total mass in the solid residue by 32% and 30%, respectively, but only reduces its oxygen requirements of combustion by about 20%. If the recovery of mineral nutrients is a primary goal in the leaching of the inedible biomass, then there may be justification in doing so, particularly if combustion ash residues are largely insoluble. Garland et al. (1988) have shown that with some pre-treatment to reduce the amount of dissolved organic carbon in the wheat straw leachate, the resulting solution was compatible with a hydroponic wheat nutrient solution.

Table 4. A Comparison of Raw Wheat Residue with Leached Wheat Residue.[1]

	Raw Wheat Residue	Leached Wheat Residue	Soluble Residue Constituents[2]
% Total Mass	100	68	32
% Ash	15.2	2.1	13.1
% Carbon	39.8	33.6	6.2
% Hydrogen	4.5	3.7	0.8
% Nitrogen	3.9	1.4	2.5
% Sulfur	0.1	0.1	0.0
% Oxygen	36.5	27.1	9.4

[1]Residue leached in deionized water for 2 hours at a rate of 50 grams per liter.

[2]From Brannon and Strayer, 1990.

Table 5. A Comparison of Raw Soybean Residue with Leached Soybean Residue.[1]

	Raw Soybean Residue	Leached Soybean Residue	Soluble Residue Constituents[2]
% Total Mass	100	70	30
% Ash	15.8	3.9	11.9
% Carbon	42.3	33.5	8.8
% Hydrogen	4.9	3.9	1.0
% Nitrogen	2.5	1.5	1.0
% Sulfur	0.1	0.1	0.0
% Oxygen	34.4	27.1	7.3

[1]Residue leached in deionized water for 2 hours at a rate of 50 grams per liter.

[2]From Brannon and Strayer, 1990.

Conclusions:

Proximate, ultimate, and heating value analysis of the IB from crops grown in the BPC can be used to estimate mass flows of carbon and oxygen in a CELSS utilizing a combustion option for converting IB directly to carbon dioxide and water. Any recovery process or combination of processes will ultimately require the same amount of oxygen to convert the biomass to carbon dioxide and water as was required to produce it. The primary difference is the amount which is converted as food within the human crew, which is the ultimate purpose for producing biomass.

The amount of oxygen from photosynthesis remaining after combustion of IB is directly related to the edible biomass/total biomass ratio or harvest index. A crop with a large harvest index (approaching unity) requires little oxygen for combustion of IB (lettuce), whereas one with a smaller harvest index (wheat and soybeans) requires much more. Other processes being studied (enzyme saccharification, fungal biomass production, aquaculture) also require oxygen, but provide additional EB.

There are trade-offs between direct combustion, which provides a direct way to recover the excess carbon and return it to the plant growth chamber, and various biological processes which increase the edible portion of the crop. Also of importance is the solubility of the ash (mineral nutrients) resulting from combustion, which must ultimately be returned to the plant nutrient solution. Future studies with the ash will indicate to what degree and with what difficulty these mineral nutrients can be recovered. Further testing of crops and recovery processes will be needed to determine which will meet the nutritional needs of the inhabitants, and optimize mass flows of oxygen and carbon dioxide in a CELSS.

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Appendix I. Conversion Calculations

1. Carbon (kg) in inedible biomass (IB) in kg = % carbon X total IB
2. Carbon (kmole) in IB = carbon (kg)/12 kg per kmole
3. Fixed oxygen (kg) in IB = % oxygen X total IB (kg)
4. Diatomic oxygen (kmole) required to oxidize carbon in IB = the number of kmoles of carbon in IB
5. Diatomic oxygen (kg) required to oxidize carbon in IB = diatomic oxygen (kmole) X 32 kg per kmole
6. Carbon dioxide produced in combusting IB = carbon (kg) in IB + diatomic oxygen (kg) required for oxidation
7. Hydrogen (kg) in IB = % hydrogen X total IB (kg)
8. Hydrogen (kmole) = hydrogen (kg)
9. Diatomic oxygen (kmole) required to oxidize hydrogen in IB = 1/4 X the number of kmoles of hydrogen in IB
10. Diatomic oxygen (kg) required to oxidize hydrogen in IB = diatomic oxygen (kmole) X 32 kg per kmole
11. Diatomic oxygen (kg) required for combustion of IB (assuming all elements except carbon and hydrogen are returned to their elemental forms) = (diatomic oxygen (kg) required to oxidize carbon in IB + diatomic oxygen (kg) required to oxidize hydrogen in IB) - fixed oxygen (kg) from IB
12. Carbon dioxide (kg) fixed during crop growth = total biomass (kg) X (30 kg per kmole for carbohydrate/44 kg per kmole for carbon dioxide)
13. Diatomic oxygen (kg) liberated during BPC crop growth was approximately = (carbon dioxide (kg) fixed/44 kg carbon dioxide per kmole) X 32 kg per mole for oxygen
14. Net diatomic oxygen from BPC crop = diatomic oxygen (kg) liberated during crop growth - diatomic oxygen (kg) required for combustion of IB

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Report Documentation Page

1. Report No. TM 103821	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Investigating Combustion as a Method of Processing Inedible Biomass Produced in NASA's Biomass Production Chamber.		5. Report Date May, 1991
		6. Performing Organization Code
7. Author(s) Dreschel, T. W., R. M. Wheeler, C. R. Hinkle, J. C. Sager, and W. M. Knott.		8. Performing Organization Report No.
		10. Work Unit No.
9. Performing Organization Name and Address The Bionetics Corporation, Mail Code:BIO-3 and The NASA Biological Research and Life Support Office, Mail Code: MD-RES-L, J. F. Kennedy Space Center, FL 32899		11. Contract or Grant No. NAS10-11624
12. Sponsoring Agency Name and Address NASA/John F. Kennedy Space Center, FL 32899		13. Type of Report and Period Covered
		14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract

The Controlled Ecological Life Support System (CELSS) Breadboard Project ath the John F. Kennedy Space Center is a research program to integrate and evaluate biological processes to provide air, water, and food for humans in closed environments for space habitation. This project focuses on the use of conventional crop plants as grown in the Biomass Production Chamber (BPC) for the production and recycling of oxygen, food, and water. The inedible portion of these crops has the potential to be converted to edible biomass or directly to the elemental constituents for direct recycling. Converting inedible biomass directly, by combustion, to carbon dioxide, water, and minerals could provide a baseline for estimating partitioning of the mass balance during recycling in a CELSS. Converting the inedible biomass to carbon dioxide and water requires the same amount of oxygen that was produced by photosynthesis. The oxygen produced during crop growth is just equal to the oxygen required to oxidize all the biomass produced during growth. Thus, the amount of oxygen produced that is available for human consumption is in proportion to the amount of biomass actually utilized by humans. The remaining oxygen must be available to oxidize the rest of the biomass back to carbon dioxide and water or the system will not be a regenerative one.

17. Key Words (Suggested by Author(s)) Inedible biomass, combustion, oxygen, carbon dioxide, biomass production.	18. Distribution Statement Unlimited

19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of pages 20	22. Price